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December 17, 2001

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"Impact Cratering Calculations"

NASA NAG5-8915
(CIT #: TJA.00005-1-NASA.000026)

Final Report

October 1, 1999 to September 30, 2000



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1. Strength and Material Response Modeling

We examined the von Mises and Mohr-Coulomb strength models with and without damage effects and developed a model for dilatancy. The models and results are given in O'Keefe et al. [2001]. We found that by incorporating damage into the models that we could in a single integrated impact calculation, starting with the bolide in the atmosphere produce final crater profiles having the major features found in the field measurements [Morgan et al., 2000]. These features included a central uplift, an inner ring, circular terracing and faulting. This was accomplished with undamaged surface strengths ~ 0.1 GPa and at depth strengths ~ 1.0 GPa.

We modeled the damage in geologic materials using a phenomenological approach, which coupled the Johnson-Cook damage model [Johnson and Holmquist, 1993] with the CTH code geologic strength model [McGlaun and Thomson, 1990]. The objective here was not to determine the distribution of fragment sizes, but rather to determine the effect of brecciated and comminuted material on the crater evolution, fault production, ejecta distribution and final crater morphology.

2. Crater Evolution

We modeled in detail the Chicxulub event [Morgan et al., 2000] from the passage through the atmosphere to the final crater formation. This work compliments the computational research in calculating the magnitudes of chemically active gases released in the impact process (e.g. Pierazzo et al. [1998], Ivanov [1996], and Pope et al. [1997]). One of the goals here is to provide a comparison of the data and calculations of the proximal and distal ejecta distributions [Koeberl and MacLeod, 2001]. We computed the crater evolution and ejecta dynamics using the CTH code [McGlaun and Thomson, 1990] and developed a mixture model [O'Keefe et al., 2001] for the sedimentary layer so as to address the effects of water saturation on the impact mechanics. We used this model to determine: 1) ejecta trajectories, 2) stratigraphic motions and final formation, 3) depth of excavation, 4) thermodynamic histories of the ejecta particles, 5) crater ejecta stages 5) the final crater morphology.

3. Ejecta Dynamics

We found the ejecta dynamics for the Chicxulub crater to be very complicated and the analytical models (e.g. the Z-model [Maxwell, 1977]) did not fit our calculations. To better understand the ejecta dynamics, we examined in separate runs, the effects of strength, damage, vaporization, and volatile content [O'Keefe et al., 2001]. All of these were found to affect the ejecta dynamics and distributions. Damage causes an increase in strength from the point of impact out to about twice the transient cavity radius. The results in a decrease in the ejecta angle as measured from the surface normal with increasing radial distance. This results in a zone of decreased ejecta blanket thickness near the edge of the excavation cavity. In the case of rock/water mixtures, there are three ejecta regions dependent upon the degree of shock heating of the volatile component. The vaporized region is boosted in ejecta velocity by the vaporization of the volatile component. We found that the Z-model [Maxwell, 1977] was only valid for the strengthless case and that strength variations due to overburden pressure or damage affected the

ejecta trajectories and that the stream tubes beneath impact surface were not stationary as required in the Z-model.

The trajectories show the effects of interactions with the projectile vapor plume and the atmosphere. The intermediate trajectories are flatter than ballistic trajectories calculated from the ejecta velocity and angle of ejection. The trajectories near the surface show effects of entrainment and fluidization.

4. Final Crater Profile

Central upliftings are a natural consequence of impacts into weak materials on planets. O'Keefe and Ahrens [1999] and always occurs in strengthless materials (fluids) and the degree of uplifting decreases with strength. When damage is modeled we found that the degree of uplifting depends primarily upon the magnitude of the internal friction in the damaged rock.

Inner rings form as a result of the collapse of the transient central peak. During collapse, the downward moving material near the top of the transient central peak collides with the upward moving material from the collapse of the transient cavity. This causes the material to mushroom outward at the collision zone for two interacting regions [Morgan *et al.*, 2000; O'Keefe and Ahrens, 1999]. In addition, the increase in dynamic pressure in the collision region increases the local strength and further promotes the development of inner rings.

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